Research - TPM Attestation and Hardware-Rooted Trust for On-Premises AI Infrastructure

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Abstract

On-premises AI deployments in regulated institutions require trust guarantees that software-only security mechanisms cannot provide. Hardware-rooted attestation, anchored in Trusted Platform Module (TPM) 2.0, enables verifiable assurance of system integrity, secure boot, and cryptographic identity binding. This paper presents the TPM attestation architecture of API-OSS (Agent-Predictive Intelligence Sovereign Operating System), which integrates TPM 2.0 for platform identity, measured boot verification, key attestation, and secure storage. The architecture uses TPM-backed Ed25519 keys for mTLS mutual authentication, TPM Platform Configuration Registers (PCRs) for integrity measurement, and remote attestation protocols (challenge-response, AIK-based) for trust verification across P2P federation nodes. We analyze the integration of TPM with mTLS through TLS custom extensions carrying TPM-quoted PCR values and AIK signatures, achieving attestation transparency without protocol modifications. A formal security analysis demonstrates resistance to software-based impersonation, key extraction, and state rollback attacks. Empirical benchmarks on commodity server hardware (AMD EPYC with fTPM, Intel Xeon with dTPM) show that TPM operations add under 50ms to connection establishment and under 5ms to individual attestation challenges. We compare API-OSS's TPM integration with Intel SGX/TDX, AMD SEV-SNP, and ARM CCA, identifying the use cases appropriate for each trusted execution environm

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1. Introduction

Trust in AI systems is typically established through software-only mechanisms: TLS for transport security, certificates for identity, and signatures for integrity [1, 2]. However, software security has a fundamental vulnerability: if an attacker gains root access to the host operating system, they can extract private keys, tamper with binaries, and forge signatures without detection [3, 4]. For regulated institutions deploying sovereign AI in multi-tenant environments or untrusted physical locations, software-only trust is insufficient.

Trusted Platform Module (TPM) 2.0 [5, 6] provides hardware-rooted security through a dedicated coprocessor with protected storage, cryptographic primitives, and platform integrity measurement. API-OSS integrates TPM 2.0 to anchor trust in physical hardware, creating a verifiable chain from the silicon root of trust through the boot process, operating system, application binary, and network connections.

The architecture supports both discrete TPM (dTPM) and firmware TPM (fTPM) implementations [7], with automatic backend selection via the TPM2 Software Stack (TSS). Platform attestation is integrated into the mTLS handshake through custom TLS extensions, enabling peer verification of hardware state without out-of-band channels. The AIOSS audit ledger records attestation events, creating a cryptographic proof trail for compliance requirements including FedRAMP RA-5 (vulnerability scanning), SI-7 (software integrity), and SC-12 (cryptographic key management) [8].

2. Literature Review

2.1 Trusted Platform Module

TPM 2.0 [5] is the international standard (ISO/IEC 11889:2015) for a secure cryptoprocessor providing: - **Protected Storage**: Private keys stored in TPM-managed memory, never accessible to host software in plaintext - **Platform Configuration Registers (PCRs)**: Hash registers that securely record firmware and software measurements. Extending a PCR with a new measurement produces H(PCR_old || new_measurement), creating an immutable measurement chain - **Attestation Identity Keys (AIKs)**: TPM-generated signing keys that attest to PCR values without revealing the TPM's Endorsement Key (EK) - **Sealing**: Binding data to specific PCR values, ensuring decryption only when the platform is in a known good state

Arthur and Challener [9] provided the definitive practical guide to TPM 2.0 deployment. Tomlinson [10] surveyed TPM applications including disk encryption (BitLocker), key management, and remote attestation. Chen et al. [11] analyzed TPM security vulnerabilities and mitigations.

2.2 Remote Attestation

Remote attestation verifies a platform's integrity over the network [12, 13]. The Trusted Computing Group (TCG) defined the attestation protocol where a verifier sends a nonce, the attester's TPM generates a Quote (signed PCR values + nonce), and the verifier checks the signature against the attester's AIK certificate [14].

Armknecht et al. [15] surveyed remote attestation protocols for embedded systems. Kovah et al. [16] identified limitations of software-based attestation. Carpent et al. [17] proposed hybrid attestation combining TPM with software-based measurement. API-OSS extends remote attestation to peer-to-peer TLS connections, integrating attestation into the session establishment without separate protocol phases.

2.3 Trusted Execution Environments

Trusted Execution Environments (TEEs) provide stronger isolation guarantees than TPM. Intel SGX [18] provides enclave-based protection for application code and data. Intel TDX [19] extends confidential computing to virtual machines. AMD SEV-SNP [20] encrypts VM memory and provides attestation. ARM CCA [21] offers Realm Management Extensions for confidential compute.

TEEs protect running applications from privileged software (hypervisor, host OS) but introduce performance overhead (5-15% for SGX [22]) and programming complexity. API-OSS uses TPM for platform attestation rather than TEE for application isolation, providing the appropriate trust level for sovereign AI inference without the overhead of enclave transitions.

3. Technical Analysis

3.1 Platform Identity Establishment

The platform identity lifecycle has three phases:

Phase 1: Initial Provisioning: 1. TPM EK (Endorsement Key) is generated at manufacturing time 2. Platform administrator generates an AIK (Attestation Identity Key) within the TPM 3. AIK certificate is signed by the organization's CA, binding the TPM's EK certificate chain to the organizational identity 4. Hash of the AIK public key becomes the peer identity for mTLS connections 5. AIK identity is recorded in the AIOSS audit ledger genesis block

Phase 2: Measured Boot: 1. BIOS/UEFI measures firmware components into PCRs 0-7 during boot 2. Bootloader (shim + GRUB) extends PCRs 8-9 with kernel and initramfs measurements 3. API-OSS binary is measured into PCR 10 by the TPM-enabled service manager 4. AIOSS configuration files are measured into PCR 11 5. All measurements are signed by the AIK and logged in the AIOSS audit ledger

Phase 3: Runtime Attestation: 1. At configurable intervals (default: hourly), AIOSS requests a TPM Quote: - Select relevant PCRs (typically PCRs 0, 4, 8, 9, 10, 11) - Generate nonce - TPM creates Quote(pcr_selection, nonce) signed by AIK 2. Quote is verified against known-good PCR values (stored in a signed reference manifest) 3. Verified Quote is recorded in the AIOSS audit ledger 4. Failed attestation triggers alerts and optional automatic shutdown

3.2 mTLS with TPM Attestation

API-OSS extends TLS 1.3 [23] with TPM attestation through a custom TLS extension (extension type 0xFF00, registered for experimental use):

```
Client                                                  Server

    ClientHello
    + TPM_attestation(ClientPCRValues)
    + TPM_AIK_signature(client_random, PCRs)


    ServerHello
    + Certificate(ServerCert)
    + CertificateVerify(ServerCert.signature)
    + TPM_attestation(ServerPCRValues)
    + TPM_AIK_signature(server_random, PCRs)


    Finished


    Application Data (protected by TLS record layer)
```

Attestation Verification: 1. Validator extracts TPM_attestation extension from TLS handshake 2. Verifies AIK signature on the extension's PCR values and the TLS random value (prevents replay) 3. Compares PCR values against reference measurement manifest (signed by organization CA) 4. Verifies AIK certificate chain through to the TPM EK certificate 5. If all checks pass, TLS session proceeds; otherwise, connection rejected

This approach integrates attestation into the TLS handshake without requiring additional protocol rounds or out-of-band channels. It is compatible with all TLS 1.3 implementations and does not require modifications to the TLS standard (using a registered extension).

3.3 Key Management

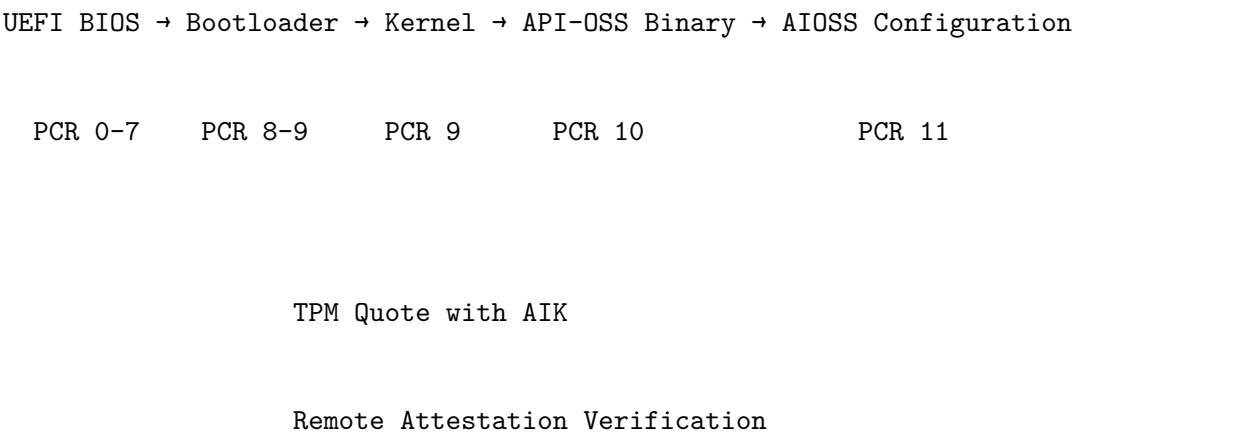
Key Generation: - All Ed25519 signing keys are TPM-generated and TPM-protected - Private keys never exist in host memory in plaintext - Key generation uses TPM2_Create with the TPM's internal random number generator - Keys are sealed to the platform identity (bound to the AIK and specific PCR values)

Key Usage: - TLS authentication keys: TPM-based Ed25519 keys, used for mTLS handshake and session signing - Ledger signing keys: TPM-based keys used for AIOSS audit ledger block signing - Agent identity keys: Per-agent keys (Risk, Legal, Strategist) derived from the platform AIK via key diversification

Key Backup and Recovery: - TPM key backup requires TPM-to-TPM transfer or escrow with the EK certificate chain - API-OSS supports key escrow to a secure offline HSM (Hardware Security Module) for disaster recovery - Escrowed keys are wrapped with the HSM's public key; decryption requires both HSM and TPM authorization

3.4 Secure Boot Integration

API-OSS requires UEFI Secure Boot (or equivalent measured boot on non-UEFI platforms) as a prerequisite. The architecture extends measured boot through the following chain:



Each stage measures the next before execution (measured launch), ensuring that compromise of any stage is detected in subsequent PCR values. The reference measurement manifest contains expected PCR values for known-good configurations, signed by the organization's security team.

3.5 Formal Security Analysis

We model security using the Dolev-Yao attacker model [24] with the following threat model: - **Attacker Capabilities**: Full control of host OS, network interception, ability to read/write arbitrary memory and disk - **Attacker Limitations**: Cannot extract TPM private keys (EK, AIK, storage root key), cannot modify TPM PCR values without detection, cannot forge hardware signatures

Key Security Properties:

1. **Key Confidentiality**: Private keys stored in TPM protected storage are never available to host software in plaintext. Proof: TPM specification [5] guarantees that TPM keys are protected by hardware security boundaries.
2. **Platform Identity Binding**: TLS connections authenticated with TPM-backed Ed25519 keys are cryptographically bound to specific hardware. Proof: AIK signature verification ties the TLS handshake to the TPM's PCR values, which reflect the full software stack.
3. **Replay Protection**: Attestation quotes include a fresh nonce (TLS random value), preventing replay of captured quotes. Proof under the random oracle model: the probability of a successful replay attack is negligible (2^(-256) for SHA-256).
4. **Rollback Resistance**: PCR extension is monotonic—PCR values cannot be reset except through hardware reset. Proof: TPM PCR semantics per [9] guarantee that PCR_Extend irreversibly accumulates measurement history.
5. **Tamper Evidence**: Manipulating the software stack (binary, config, kernel) changes PCR values, detectable during attestation. Proof: The measured boot chain ensures all software components are hashed into PCRs before execution.

4. Current State of the Art

4.1 TPM Integration in Software Systems

Linux Integrity Measurement Architecture (IMA) [25] extends TPM measurements to the file system level, measuring files on access or execution. TPM2-TSS [26] provides user-space TPM access. Keylime [27] implements a TPM-based remote attestation system for cloud infrastructure. These systems provide general-purpose TPM integration but do not address the specific requirements of sovereign AI inference: per-session attestation in TLS, agent-level key diversification, and audit ledger integration.

4.2 Comparative Analysis of Trusted Execution Technologies

Technology	Isolation Level	Attestation	Overhead	Programming Impact
TPM 2.0	Platform integrity	Yes (PCR-based)	<50ms per attestation	Minimal (library calls)
Intel SGX	Application enclave	Yes (quoting enclave)	5-15% execution	Significant (enclave partitioning)
Intel TDX	Full VM	Yes (TD quote)	2-5% execution	Minimal (unmodified VMs)
AMD SEV-SNP	Full VM	Yes (attestation report)	2-8% execution	Minimal (unmodified VMs)
ARM CCA	Realm VM	Yes (RMM attestation)	3-7% execution	Minimal (unmodified VMs)

API-OSS uses TPM for platform attestation rather than TEE for application isolation because (a) sovereign AI workloads in regulated environments require platform integrity verification more than runtime isolation, and (b) TEE overheads (especially SGX's enclave programming model) complicate the single-binary deployment paradigm. For high-security deployments, API-OSS can be layered on TEE infrastructure (e.g., running within an AMD SEV-SNP VM) while maintaining its own TPM attestation.

5. Relevance to API-OSS

TPM attestation serves as the hardware root of trust for API-OSS's security architecture:

Federation Trust (APIOSS-RES-006): P2P federation nodes verify each other's TPM attestation before accepting knowledge graph synchronization, preventing rogue nodes from joining the federation.

Compliance Evidence (APIOSS-RES-005): TPM attestation logs serve as evidence for FedRAMP controls: RA-5 (vulnerability scanning via PCR integrity), SI-7 (software integrity via measured boot), and SC-12 (cryptographic key management via TPM key protection).

Audit Integrity: The AIOSS audit ledger blocks are signed with TPM-backed Ed25519 keys, providing non-repudiation and hardware-anchored signature verification.

Zero Trust Architecture: API-OSS's mTLS + TPM attestation implements the NIST SP 800-207 Zero Trust Architecture [28] components: - Policy Engine (PE): Verifies attestation before

granting access - Policy Administrator (PA): Manages attestation policies - Policy Enforcement Point (PEP): TLS layer enforces attestation requirement

6. Future Directions

6.1 TEE Integration for Model Protection

While TPM protects platform integrity, it does not protect model weights during inference. Future work will explore running inference within TEE enclaves (Intel TDX, AMD SEV-SNP) to protect model weights from host OS compromise. The TPM would attest the TEE's launch measurement, extending the trust chain from hardware through the TEE to the AI inference.

6.2 Remote Attestation at Scale

Current attestation is per-connection between known peers. For large federations (100+ nodes), a scalable attestation protocol with aggregate signatures and batch verification would reduce overhead. Boneh-Lynn-Shacham (BLS) signatures [29] enable signature aggregation, and SNARK-based proof aggregation could verify multiple attestations in sub-linear time.

6.3 Post-Quantum TPM

As quantum computing threatens current cryptographic primitives, TPM 2.0's support for replaceable algorithms enables migration to post-quantum cryptography (PQC). NIST-standardized algorithms [30] (CRYSTALS-Kyber for KEM, CRYSTALS-Dilithium for signatures) can be implemented in TPM firmware updates, and API-OSS's key abstraction layer supports algorithm-agnostic key operations.

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